Reducing nitrogen pollution while decreasing farmers’ costs and increasing fertilizer industry profits

David R. Kanter, Xin Zhang and Denise L. Mauzerall

Supplementary materials

These supplementary materials provide more details on several elements of our paper:

1. Past trends in fertilizer rates and corn yields in the USA and China.
2. Methods and data sources used to project future fertilizer prices and production costs and their evaluation.
3. More detail on the assumptions underpinning the USA and China nitrogen use efficiency (NUE) baselines.
4. An explanation of the central factors driving the differences in NUE between the USA and China.
5. Details on the price and production cost estimates for fertilizer best management practices (FBMPs).
6. Details on current EEF consumption.
7. The expert elicitation questionnaire used to generate values for EEF price and cost of production, and a summary of the results.
1. Past trends in fertilizer rates and corn yields in the USA and China

While average N application rates for corn grown in the USA increased by 6% over the period 1990-2010 (from 148 kg N ha\(^{-1}\) to 157 kg N ha\(^{-1}\)), corn yields increased by 30% (from 7.4 Mg ha\(^{-1}\) to 9.6 Mg ha\(^{-1}\)), indicating a notable increase in US NUE due to improved germplasm and crop management practices (Cassman et al. 2002; Dobermann and Cassman, 2004; USDA ERS, 2011, 2014). By contrast, over the same period Chinese farmers in the corn sector have increased their average N fertilizer rates by 46% (from 157 kg N ha\(^{-1}\) to 230 kg N ha\(^{-1}\)), and increased yields by 20% (4.5 Mg ha\(^{-1}\) to 5.5 Mg ha\(^{-1}\)), which has led to a decrease in Chinese NUE (FAOSTAT, 2013). These differing trends are captured in Fig. S1, which shows kg N applied per Mg of corn produced, indicating that the amount of N used to produce one Mg of corn is decreasing in the US and increasing in China.

[Insert Fig. S1 here]
2. Future fertilizer prices and production costs

Projecting future fertilizer prices

United States

For the purposes of this study, we create an aggregate US N fertilizer price, based on the relative consumption of urea, anhydrous ammonia and urea ammonium nitrate (UAN) over the period 2000-2010. These three fertilizers comprise 92% of the N fertilizer consumed in the US (USDA ERS, 2013a). We assume their relative consumption (28% urea, 37% anhydrous ammonia, and 35% UAN – proportions which fluctuated less than 2% during the period 2000-2010) remains constant over the period of the analysis. To estimate future prices an autoregressive integrated moving average (ARIMA) model was developed using the principal determinants of N fertilizer prices - historical natural gas, corn and wheat prices from 1980-2012 (IBISWorld, 2012; Yara, 2012):

\[ \begin{align*}
    P_N &= -25.3 + 13.63(P_{ng}) + 0.60(P_C) + 1.03(P_W) \\
\end{align*} \]  

\( P_N = \text{Nitrogen fertilizer price ($ kg N^{-1})} \)

\( P_{ng} = \text{Natural gas price ($ MMBTU^{-1})} \)

\( P_C = \text{Corn price ($ Mg^{-1})} \)

\( P_W = \text{Wheat price ($ Mg^{-1})} \)
This simple model’s simulation of historical U.S. N fertilizer prices is relatively well correlated with historical US Geological Survey ammonia prices ($r^2=0.56$, $p<0.01$; USGS, 2012) and World Bank urea prices ($r^2=0.67$, $p<0.01$; World Bank, 2013). Coal and rice prices were not included in the final model as they decreased the correlation coefficient. To estimate future N prices, projected wheat, corn and natural gas prices from the OECD/FAO and IEA are inserted into Equation S1. These price estimates are summarized in Table S1a.

**China**

Urea comprises 67% of China’s fertilizer consumption. This proportion is expected to increase as ammonium bicarbonate (which currently comprises 19% of consumption) is gradually phased out (Yara, 2012). A series of recent market reforms in China (Zhang et al. 2009) have led to Chinese urea prices being increasingly correlated with world urea price fluctuations. Since 1996, Chinese urea prices have been highly correlated with World Bank urea prices ($r^2=0.79$, $p<0.01$). We therefore assume that China’s future urea prices will equal future World Bank urea prices.

To estimate future World Bank urea prices, we developed another ARIMA model using historical natural gas, coal, corn, rice and wheat prices from 1980-2012:

$$P_{\text{urea}} = -138.07 + 1.03(P_{\text{coal}}) + 14.18(P_{\text{ng}}) + 0.42(P_c) + 0.2(P_r) + 0.56(P_w) \quad (S2)$$
This simple model’s simulation of historical World Bank urea prices is well correlated with historical USDA urea prices ($r^2=0.72$, $p<0.01$; USDA ERS, 2013b) and US Geological Survey ammonia prices ($r^2=0.75$, $p<0.01$; USGS, 2012). In contrast to the US fertilizer price model, including coal and rice prices here increases the correlation coefficient, because of coal’s primacy as an energy and hydrocarbon source in Chinese fertilizer production, and the large proportion of Chinese agriculture devoted to rice production. To estimate future urea prices, projected crop and energy prices from the OECD/FAO and IEA are inserted into Equation S2. These price estimates are summarized in Table S1b.

**Projecting future fertilizer production costs**

**United States**

The cost of production for the major forms of N fertilizer used in the US (anhydrous ammonia, urea and UAN) is calculated under the assumption that natural gas will account for 75-90% of the cost of ammonia production (GAO 2003; Huang 2007; IBISWorld, 2012) and it takes, on average, 36 million British thermal units (MMBtu) to make one Mg of ammonia (Yara, 2012):

\[
\text{Ammonia production cost (} \text{Mg}^{-1}) = \frac{36 \times P_{ng}}{S} \tag{S3}
\]

\[P_{ng} = \text{Natural gas price (} \text{MMBtu}^{-1})\]
\( S = \) Scaling factor that increases linearly from 0.75 (when \( P_{ng} \) is \$2 \text{ MMBtu}^{-1} \) to 0.9 (when \( P_{ng} \) is \$8 \text{ MMBtu}^{-1} \). This scaling factor also implicitly takes into account the other costs of ammonia production not mentioned here, including labor and regulatory costs, plant facility maintenance, transport and other associated expenditures (Yara, 2012).

This cost estimate is subsequently adapted to estimate the urea and UAN cost of production, based on the amount of N needed from ammonia to produce 1 Mg of product (it typically takes 0.37 tons and 0.58 tons of ammonia to make 1 ton of UAN and urea, respectively – Yara, 2012) and the additional energy required to convert ammonia to urea and UAN (5.2 MMBtu for urea and 1.4 MMBtu for UAN – the equations below are adapted from Sawyer et al. 2010; Yara, 2012):

\[
\text{Urea production cost (} \text{\$ Mg}^{-1} \text{)} = \frac{0.58 \times (36 \times P_{ng}) + 5.2 \times P_{ng}}{S} \quad (\text{S4})
\]

\[
\text{UAN production cost (} \text{\$ Mg}^{-1} \text{)} = \frac{0.38 \times (36 \times P_{ng}) + 1.4 \times P_{ng}}{S} \quad (\text{S5})
\]

As with the fertilizer prices, the cost estimates of these three forms of N fertilizer are then aggregated based on their weighted consumption to create an overall cost of N fertilizer production.
In China, 92% of ammonia production uses either coal (71%) or natural gas (21%) – the remaining 8% from oil is being gradually replaced by coal and gas (Zhou et al. 2010). Both Chinese coal and natural gas prices have become increasingly correlated with world prices. Recent Chinese coal price data from 1996 to 2012 indicates that they were highly correlated with World Bank coal prices \( (r^2=0.91, p<0.01) \). Similarly, China’s natural gas prices were highly correlated with Japanese liquefied natural gas (LNG) prices over the same period \( (r^2=0.90, p<0.01) \), with both countries importing much of their LNG from Southeast Asia (US EIA, 2014). However, the Chinese fertilizer industry receives a considerable government subsidy for LNG, making it significantly more affordable: the 2007-2012 ratio of LNG prices paid by the Chinese fertilizer industry vs. Japanese LNG prices was approximately 0.5 (LBNL, 2008; World Bank, 2013). This ratio is assumed to remain constant for the period of analysis.

With this in mind, the following assumptions are made in projecting future urea production costs: i) Chinese natural gas prices will continue to track Japanese LNG price fluctuations, taking into account the 50% subsidy the Chinese fertilizer industry receives for natural gas; and ii) Chinese coal prices will equal world prices by 2020 as coal is not subsidized for China’s fertilizer industry (Zhang et al. 2009).
**Chinese natural gas-based fertilizer production**

Given that large, more energy efficient plants dominate China’s natural gas-based fertilizer production, in contrast to the less efficient small and medium sized plants where coal-based production dominates, the same cost structure as that for US natural gas-based production is used to estimate the cost of gas-based fertilizer production (Zhou, 2010; Zhang et al. 2013).

**Chinese coal-based fertilizer production**

For coal-based ammonia production, coal prices are estimated to be 50-70% of the cost of production (Kjellberg et al., 2012; PotashCorp, 2013). The energy required to produce 1 ton of ammonia using coal is 59.4 GJ/Mg NH₃, with anthracite (comprising approximately 80% of the coal used in ammonia production,) providing 27.2 GJ/Mg (Kahrl et al. 2010). An additional 12.2 GJ is required to produce 1 Mg of urea. We assume that these energy consumption estimates remain constant for the period of analysis (2015-2035) because coal-based ammonia production in China is largely limited to small- and medium-scale facilities, which are more energy intensive than large-scale facilities and have not seen a statistically significant increase in energy efficiency in recent years (Zhou et al. 2010; Zhang et al. 2013). This is a conservative assumption, as increases in the energy efficiency of coal-based ammonia production could reduce production costs for the fertilizer industry, thereby potentially increasing their profitability. Using a similar scaling factor as the one applied to natural gas-based
production, we estimate the cost of coal-based urea production using the following equation:

$$\text{Urea cost per Mg} = \frac{0.59 \times \left( \frac{59.4}{27.2} \times P_{\text{coal}} \right) + 12.2 \times P_{\text{coal}}}{S}$$

(S6)

$P_{\text{coal}}$ = Coal price ($\text{Mg}^{-1}$)

S = Scaling factor increasing linearly from 0.5 (when coal prices are $60 \text{ Mg}^{-1}$ or below) to 0.7 (when coal prices are $110 \text{ Mg}^{-1}$) (Kjellberg et al., 2012; PotashCorp, 2013). This scaling factor also implicitly takes into account the other costs (and subsidies – see Supplementary Materials Section 10) of ammonia production, akin to the scaling factor for natural gas-based production.

Combining the two cost structures

In order to create one cost estimate for urea production, the cost estimates for coal and natural gas-based production are combined in proportion to their use by the Chinese fertilizer industry. With oil-based ammonia production projected to become obsolete in the near future (Zhou, 2010), we assume a fixed proportion of 77% coal and 23% natural gas-based production through 2035.
3. NUE baselines for the USA and China

United States

As described in the main text, this study estimates an average N recovery efficiency (RE) of 40% for the USA corn sector in 2010-2012. This implies that only 63 kg N ha\(^{-1}\) of the 157 kg N ha\(^{-1}\) applied on average to US corn in 2010 (with a standard deviation of 123-191 kg N ha\(^{-1}\) – USDA 2011) was recovered by the corn plant. We assume corn N uptake from unfertilized fields remains constant over space and time at 78 kg N ha\(^{-1}\), though in reality indigenous soil N supply varies widely across US corn cropland (from 39 to 280 kg N ha\(^{-1}\) according to Cassman et al. 2002). The value used in this study is the mean value taken from 698 sites across Illinois, Iowa, Minnesota, and Wisconsin (Joern and Sawyer, 2006). The 2010-2012 RE baseline is slightly higher than the mean of 37% calculated by Cassman et al. (2002) for the late 1990s, a study which estimated a wide range of RE values across US corn cropland (7%-67%).

China

The main text also describes this study’s estimate of an average RE of 11% for China’s corn sector in 2010-2012. In other words, only 25 kg N ha\(^{-1}\) of the 230 kg N ha\(^{-1}\) applied on average to Chinese corn in 2010 (with a standard deviation of 89-373 kg N ha\(^{-1}\) – Zhang et al. 2013) was recovered by the corn plant. We assume corn N uptake from unfertilized fields remains constant over time and space at 54 kg N ha\(^{-1}\). However, as
with the US, indigenous soil N supply varies widely across Chinese corn cropland (from 28 to 174 kg N ha\(^{-1}\) according to Cui et al. 2008). The value used in this study is the mean value taken from a study across 14 sites in China (Chen et al. 2010). The 2010-2012 RE baseline is similar to the 15% RE cited as the mean for traditional farmer practices (ranging from 1%-34%) in Cui et al. (2008).

4. Accounting for the differences in NUE between the United States and China

A number of factors are responsible for the substantial difference in average RE estimated for China (11%) and the US (40%). Chinese and US corn farmers differ considerably in their management practices and relationship to the land. Farm size is vastly different, with corn farms in China averaging 0.5 hectares, while US corn farms average 100 hectares (Meng et al. 2006; USDA ERS 2014a). This is partly due to the fact that private ownership of agricultural land does not currently exist in China – agricultural land is collectively owned, with land parcels determined by family size (approximately one fifteenth of a hectare per capita), and land contracts issued by village leaders for 15-30 years (Rozelle and Huang, 2001). While farmers are supposed to have complete use and income rights during this contract period, these rights are not always secure, with village officials largely free to take the land back and convert it to industrial and commercial uses (Liu et al. 1998, Roberts, 2013). The inability of farmers to privately own agricultural land has been shown to create a disincentive in investing in improved crop and soil management practices, and instead frequently encourages unsustainable
practices with short-term payoffs, such as the over-application of N fertilizer (Lohmar and Somwaru, 2012). The Chinese central government recognized this issue during President Xi Jinping’s third plenum in November 2013 and has committed to begin gradual reforms aimed at creating private ownership of agricultural land (Hong, 2013; Silk 2013). By contrast, virtually all farmland in the US is privately owned, with 29% rented out to farmers by non-operating landowners (Nickerson et al., 2012).

In terms of farm costs, fertilizer expenditure as a proportion of total farm cost is comparable in both countries, making up 21% of total farm costs in both China (16%-26% range across provinces) and the US (14%-28% range across regions) (USDA, 2014b; Hu and Zimmer, 2013). However, labor costs are vastly different, making up 39% of total farm costs in China (23%-57% range across provinces) and 6% in the US (4%-8% range across regions), with mechanization levels much higher in the US compared to China. In terms of N management practices, there appears to be little widespread adoption in China (Meng et al. 2006), while in the US, 16% of farmers over the period 2005-2010 reported managing N more carefully (a term referring to more “appropriate timing and method of [N] application” – Ribaudo et al. 2011), with 14% of farmers reducing their N use by 28% on average (Ribaudo et al. 2012). Several other issues contributing to the lower RE in China versus the US include low-quality and/or costly seeds, the sale of fake fertilizer and pesticide (and the inability of farmers to detect them), differences in soil quality, and a lack of access to information on improved management practices and the technology to implement them (Meng et al. 2006; Ma et al. 2013).
5. Details on FBMP price and provision costs

While there are initial fixed costs for farmers to implement FBMPs (such as learning new management techniques), the IIASA cost estimates listed in Table S2 (optimized to achieve the N rate reductions prescribed by each RE target) only consider variable operating costs such as labor, energy and materials, and are reported in $ kg N$^{-1}$ reduced.

[Insert Table S2 here]

Actions that farmers already take to improve NUE are integrated into the BAU scenario. For example, since 2001 16% of US farmers have reduced their N application rate by an average of 22%, and 7% have used precision N application (USDA ERS, 2013c). As there has been no clear trend in the adoption of these practices over this period, these proportions are kept constant out to 2035 in the BAU scenario and used as a baseline in the NUE scenarios; by contrast, there is no evidence that FBMPs are widely implemented in China. Consequently, the price estimates listed in Table S2 in the main paper reflect the cost of implementing additional measures to achieve the RE targets.

The two FBMPs considered here are split application and precision application. Split application refers to the application of smaller fertilizer doses throughout the growing season that coincide with the times that the crops most need N, a practice which is estimated to reduce N requirements by 11% according to GAINS. Precision application uses GPS technology and soil testing to identify more precisely where the N requirements are in a particular field, and is estimated to reduce N requirements by 33% according to
GAINS (Robertson and Vitousek, 2009). The ratio of split to precision application in Table 2 is determined by the N rate reduction required by a particular RE target.

6. Current EEF consumption

Current levels of EEF use are already integrated into the baseline of each scenario, as is done with the FBMP cost estimates. For example, N inhibitors (i.e. either nitrification or urease inhibitors) were applied to approximately 12% of US corn cropland in 2010 (USDA ERS, 2013c) – this level is kept constant in the BAU scenario (indeed, it has been relatively constant since 1996, with the proportion of corn production receiving N inhibitors ranging from 8.5%-12.5% and no clear trend over time) and serves as a baseline in the NUE scenarios. As with FBMPs, there is no evidence of widespread use of EEFs in China’s corn cropland.

7. Expert elicitation questionnaire

Due to the sensitive nature of this information, the identities of these experts are anonymous – though each expert has given their permission for their estimates to be included in the analysis. The results of the elicitation and included at the end of this questionnaire.
Project description

The objective of this interview is to elicit your judgment on the effectiveness, price, and cost of production of enhanced efficiency fertilizers (EEFs) and how they might vary under different nitrogen (N) management policies in the US corn sector. For the purposes of this project, EEFs refer to slow/controlled-release fertilizers and nitrification and urease inhibitors. Specific data needs include:

1. N rate reduction potential using EEFs
2. Current price and cost of production of EEFs
3. Future price and cost of production of EEFs under two N management scenarios

Because the data to address these requirements are either inconsistent or not available from published sources or existing databases, estimates are being obtained through this expert elicitation.

This document is structured as follows:

- The first section defines the main terms and acronyms used in this elicitation.
- The second section is the elicitation itself, split into three parts: questions on N rate reduction potential, current EEF prices and production costs, and future EEF prices and production costs under the N management scenarios.
- The final section outlines the data sources, methodology, and assumptions of the cost-benefit analysis (CBA) that this elicitation feeds into. This is intended as background material.¹

 Definitions & acronyms

**Fertilizer industry:** All economic actors along the N fertilizer supply chain before it reaches the farmer - from ammonia producers, to fertilizer manufacturers, to retailers.

**Nitrogen use efficiency:** For the purposes of this project, nitrogen use efficiency (NUE) refers to fertilizer recovery efficiency (the proportion of N fertilizer applied that is recovered by the crop):

\[
RE = \frac{U-U_0}{F} \times 100
\]

(11)

U = Total corn N uptake in a plot that received fertilizer (lb N/acre)

U₀ = Total corn N uptake in a plot that received no fertilizer (lb N/acre)

F = Fertilizer applied (lb N/acre)

¹ This background material was a compilation of the fertilizer price/production cost projection methods (Supplemental Materials Section 2) and the discussion of NUE estimates and assumptions (Supplemental Materials Section 3), and so is not repeated here.
**Slow/controlled release fertilizer (SCRF):** For the purposes of this project, the term slow/controlled release fertilizer refers to substances that release N via the decomposition of low-solubility compounds (e.g. urea formaldehyde (UF) and isobutylidene-diurea (IBDU)), and substances that control N release via a physical barrier (e.g. organic or inorganic coatings).

**Nitrification inhibitor (NI):** A substance that inhibits the biological oxidation of ammonium (NH$_4^+$) to nitrate (NO$_3^-$), extending the time the N component of the fertilizer remains in the soil as NH$_4^+$.

**Urease inhibitor (UI):** A substance that inhibits urea hydrolysis to NH$_4^+$, extending the time the N component of the fertilizer remains in the soil as urea.

**Questions**

In this section of the elicitation, I will ask you to provide your estimates of likely values, based on your expertise, for the following parameters:

- Current price and cost of production of EEFs
- Future price and cost of production of EEFs under two N management scenarios

---

2 For the sake of length, we only include the questions asked to US experts. The only difference with the questions for Chinese experts is the questions on future prices and production costs, where we describe China’s nitrogen use efficiency targets.

3 In an earlier draft of the elicitation there was a third parameter: N rate reduction potential, i.e. how much N application rates could be reduced by using an EEF while still maintaining the same yield. However, we decided to use published literature values for this parameter.
The preambles to the questions below should frame your responses, and the additional material in [the background material] provides information on the data, assumptions and methodology underpinning the cost-benefit analysis that this elicitation feeds into. The values you offer should reflect your uncertainty, such that:

- The 5% uncertainty bound indicates a 1 in 20 chance that the value is lower
- The 95% uncertainty bound indicates a 19 in 20 chance that the value is lower
- The 50% uncertainty bound indicates that the value is equally likely to be lower or higher

**Current price and cost of production**

**Current price**

A wide range of price estimates for SCRFs and NIs/UIs exist in the literature. The SCRF premium ranges from 50%-1200% above the price of traditional N fertilizer (Lammel, 2005, Trenkel 2010, Blaylock 2013), while the NI/UI premium is estimated to be slightly lower at 8%-100% (Lammel 2005, Laboski 2006, Trenkel, 2010, Brink et al. 2011).
Focusing on broad-acre crops in particular, what in your judgment is the average premium currently charged (in percentage terms) above the price of traditional N fertilizers for SCRFs and NI/UIs, respectively?

*Nitrification and urease inhibitors*

5%___________ 95%___________ 50%___________

*Slow/controlled-release fertilizers*

5%___________ 95%___________ 50%___________

**Current cost of production**

How much more on average per ton of N does it currently cost to produce a SCRF or a fertilizer supplemented with NIs/UIs vs. traditional N fertilizer (in percentage terms)?

*Nitrification and urease inhibitors*

5%___________ 95%___________ 50%___________

*Slow/controlled-release fertilizers*

5%___________ 95%___________ 50%___________

**Future price and cost of production**

A business-as-usual scenario and two improved N management scenarios are described in [the background material], with the latter based on fertilizer recovery efficiency (RE) targets to be achieved by 2035. With RE for corn in 2010-2012 estimated to be 40%, the
first N management scenario sets a RE target of 50%, the second sets a RE target of 60% (considered the upper limit of the fertilizer recoverability of US corn – Smil, 1999; Kitchen and Gould, 2001; Dobermann, 2007). It is assumed that FAO’s projected rate of corn yield increase remains constant across the two scenarios – the only thing that changes is the N application rate. While several strategies to implement these targets are considered in the cost-benefit analysis that this elicitation feeds into (including behavioral practices such as precision and split N application), the present focus is on the 100% EEF implementation strategy.

**RE 50%**

In the RE 50% scenario, farmers would have to reduce their fertilizer N rates by 10% in 2035 compared to the business-as-usual scenario.

If SCRFs and NI/UIs can reduce N rate requirements by 37-38%, they would have to constitute 32% of the N applied to achieve the RE target. If SCRF and NI/UI use is split 50/50 by US corn farmers in 2035, SCRF consumption of ~60,000 N tons and NI/UI use of ~840,000 N tons in 2010 (Landels, 2013) will each have to increase to 900,000 N tons by 2035.
How would this expansion in demand affect the prices of NIs/UIs and SCRFs? Give your answer in percentage terms relative to your present-day price estimate.

*Nitrification and urease inhibitors*

<table>
<thead>
<tr>
<th>Percentage</th>
<th>5%</th>
<th>95%</th>
<th>50%</th>
</tr>
</thead>
</table>

*Slow/controlled-release fertilizers*

<table>
<thead>
<tr>
<th>Percentage</th>
<th>5%</th>
<th>95%</th>
<th>50%</th>
</tr>
</thead>
</table>

Is the assumption of a 50/50 split between SCRF and NI/UI use reasonable? If not, what in your judgment is a more realistic partitioning?

How would this expansion affect the cost of NI/UI and SCRF production? Give your answer in percentage terms relative to your present-day production cost estimate.

*Nitrification and urease inhibitors*

<table>
<thead>
<tr>
<th>Percentage</th>
<th>5%</th>
<th>95%</th>
<th>50%</th>
</tr>
</thead>
</table>

*Slow/controlled-release fertilizers*

<table>
<thead>
<tr>
<th>Percentage</th>
<th>5%</th>
<th>95%</th>
<th>50%</th>
</tr>
</thead>
</table>
RE 60%

In the RE 60% scenario, farmers would have to reduce their fertilizer N rates by 25% in 2035 compared to the business-as-usual scenario.

If SCRFs and NI/UIs can reduce N rate requirements by 37-38%, then they would have to constitute 72% of the N applied to achieve the RE target. If SCRF and NI/UI use is split 50/50 by US corn farmers in 2035, SCRF consumption of ~60,000 N tons and NI/UI use of ~840,000 N tons in 2010 (Landels, 2013) will each have to increase to 1.7 million N tons by 2035.

<table>
<thead>
<tr>
<th>How would this expansion in demand affect the prices of NIs/UIs and SCRFs? Give your answer in percentage terms relative to your present-day price estimate.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrification and urease inhibitors</td>
</tr>
<tr>
<td>5% __________________ 95% __________________ 50% _______</td>
</tr>
<tr>
<td>Slow/controlled-release fertilizers</td>
</tr>
<tr>
<td>5% __________________ 95% __________________ 50% _______</td>
</tr>
</tbody>
</table>
How would this expansion affect the cost of production of NIs/UIs and SCRFs? Give your answer in percentage terms relative to your present-day production cost estimate.

*Nitrification and urease inhibitors*

5% ______________  95% ______________  50% ______________

*Slow/controlled-release fertilizers*

5% ______________  95% ______________  50% ______________

Is the assumption of a 50/50 split between SCRF and NI/UI use reasonable? If not, what in your judgment is a more realistic partitioning?

**Miscellaneous**

Do you have other colleagues you would recommend as interview subjects for this research?
Results

[Insert Table S3 here]

8. Seed questions

Below are the seed questions used to evaluate the weight to give each expert’s responses. Questions 4 and 5 are different for the US and China due to differences in data availability to verify answers.
United States

1. How many years have you worked in, or has your research focused on, the US fertilizer industry?

2. Do you work directly on the subject of EEFs? Does your company produce EEFs? If yes, for how long?

3. What proportion of SCRF demand in the US is for agricultural land, as opposed to professional and consumer markets such as golf courses and turf?

4. What was the portion of US corn cropland using nitrogen inhibitors (either nitrification or urease) of some kind in 2010?

5. How many North American companies produce nitrification inhibitors?

China

1. How many years have you worked for, or has your research focused on, the Chinese fertilizer industry?
2. Do you work directly on the subject of EEFs? Does your company produce EEFs? 
   If yes, for how long?

3. What proportion of SCRF demand in China is for agricultural land, as opposed to 
   professional and consumer markets such as golf courses and turf?

4. What was the first major product added to a fertilizer to delay the release time of 
   nitrogen in China? When was it first marketed?

5. How many Chinese companies produce controlled-release fertilizers?

**Weighting protocol for seed questions**

An example of the protocol for weighing the expert responses is included in Table 1 for 
the United States. The highest weighting an expert could receive for a response was 1 and 
the lowest weighting was 0.5. For example, Q1 for the US asked how many years an 
expert had worked in the US fertilizer industry; if the response was less than five years, 
the expert was given a weight of 0.5, between 5 to 10 years a weight of 0.6, and so on 
until the response “over 25 years” would receive a weighting of 1. Q4 asked what portion 
of US corn cropland used nitrogen inhibitors of some kind in 2010. The correct answer is 
12% - if the expert response was within the 10%-15% range, they were given a weight of 
1, if it was in the 5%-10% range or the 15%-20% range their response was given a weight 
of 0.8 and so on. If they didn’t know, they were given a weight of 0.5. Table S1
summarizes the correct answers for each question (where applicable), the range of answers given by the experts, and the average of the weightings for each set of responses.

[Insert Table S4 here]

9. Summary of the environmental costs

IPCC emission factors for N pollution and environmental damage estimates are summarized in Table S5. The monetized environmental benefits of the various RE targets are then compared to their economic impacts on farmers and the fertilizer industry in Table S6.

[Insert Table S5 here]

[Insert Table S6 here]

10. Policy context

While this study has not attempted to identify the optimal policy mechanisms that could be used to implement the NUE targets in both the US and China, the following section provides the policy context for each country, with several suggestions of potential instruments to realize the RE targets.
US agricultural policy regarding the environment consists of several programs and policy mechanisms that could potentially be harnessed to implement improved N management policies. The 1985 Food Security Act was one of the first instances of a US agricultural policy with an explicit environmental focus, mandating that farmers that receive federal crop subsidies on highly erodible land implement soil conservation measures (a policy instrument implicitly emulated in the RE scenarios). This increasing awareness of agriculture’s environmental impacts continued with the 1996 Food and Agriculture Improvement Act, which created the Environmental Quality Incentives Program (EQIP), a voluntary program that provides farmers with technical assistance and cost-sharing/incentive payments to lessen their farm’s environmental impacts. N management (under the broader umbrella of “nutrient management”) is one of the activities eligible for EQIP funding (USDA NRCS, 2004). Yet, despite these programs, funding for technical assistance has remained approximately constant since the mid 1960s (USDA, 2000). This underfunded technical infrastructure has led to a number of issues hampering the implementation of nutrient management practices: from a lack of government funding for agronomic research and technology development, to insufficient education and extension services to help farmers learn about and implement environmentally responsible management practices. Many believe this issue has become the most important obstacle to improving environmental management in US agriculture (Cox, 2007).

There are several ways forward for US agricultural policy in this area. For example, the compliance mechanisms used for controlling soil erosion could be applied to N
management (i.e. federal crop subsidies tied to farmers having a comprehensive nutrient management plan). Indeed, the compliance mechanism has proven to be the most effective policy instrument in US agricultural policy: between 1982 and 1997 soil erosion on US cropland was reduced 40%, with 25% of this reduction directly attributable to the soil conservation compliance mechanisms (Claassen, 2004). Another important option is increasing the USDA’s technical and educative capacity, because much of the conservation effort on private land is done by farmers not receiving payments for doing so, indicating that cost may not be the primary barrier to wider use of conservation practices. Instead, technical assistance and education can be done at lower cost, and are likely to stay in place without ongoing subsidies (Cox, 2007).

It is unclear what the impact of a fertilizer tax would be given the wide range of estimates of elasticity of demand (i.e. how farmers change their behavior in response to a price increase), varying between -0.2 and -1.87 (Williamson, 2011) – meaning that a 10% increase in fertilizer price has been estimated to reduce farmers’ fertilizer demand between 2% to 18.7%. However, subsidies to incentivize EEF use could be effective as they have been when government has sought to promote the use of a new, initially costly technology (e.g. Chen, 1996; Jaffe et al. 2004).

In contrast to farmers, the US fertilizer industry receives little financial assistance (aside from various governmental grants encouraging environmental R&D), and is instead subject to a suite of environmental regulations, including the Clean Air Act, Clean Water Act and the Safe Drinking Water Act (that limit the air and water pollutants allowed to be emitted from their production facilities) as well as state-specific regulations. The industry is highly concentrated, with three companies making up 75.1%
of the market (Agrium Inc. (45.6%), The Mosaic Company (10.5%), and Potash Corporation (10%) – IBISWorld, 2013a). While Mosaic does not sell N fertilizer, Agrium and Potash Corp. do, with a selection of both traditional and enhanced efficiency fertilizers. Though several smaller companies produce EEFs (e.g. Everris, Florikan etc.), they focus solely on specialty crops. A massive increase in EEF production is required if EEFs are to be a viable option for farmers to achieve NUE targets. Only major companies that already have well-established production capacity and capital to invest in R&D can arguably achieve this increase, because barriers to entry in the fertilizer industry are high. For example, N fertilizer plants with a production capacity of one million metric tons of N products cost between $700 million and $1 billion and take two to three years to build (IBISWorld, 2013a). As mentioned in the introduction in the main text there is a potential opportunity for these major companies, analogous to the one provided to the ODS and pesticide producers; they could be both the producer of the regulated product (traditional N fertilizer) and the provider of a more sustainable, profitable alternative (EEFs) – a valuable market opportunity.

China

In contrast to the environmental management measures that have characterized US agricultural policy since the 1980s, the emphasis of Chinese agricultural policy has been to safeguard food security by ensuring fertilizer availability and affordability. Consequently, China’s fertilizer subsidy for farmers increased from $15 billion in 2006 to $105 billion in 2010. The artificially low market prices that result are a major cause,
some believe, of the inefficient use of fertilizer by a majority of Chinese farmers (Li et al. 2013). The subsidies have dramatically increased fertilizer production from 0.5 Tg N in 1961 to 38 Tg N in 2011; similarly N fertilizer application rates have increased from 3 kg N ha\(^{-1}\) in 1961 to 196 kg N ha\(^{-1}\) in 2010 (FAOSTAT, 2013).

Furthermore, China has not only provided financial assistance to its farmers, but also, in contrast to the US, to its fertilizer industry. Indeed, during more than three decades of state ownership, government investment in the fertilizer industry (via a series of subsidies) accounted for 40% of the total monetary investment in China’s entire chemical industry (Li et al. 2013). A further contrast with the US fertilizer industry is a low level of concentration: four companies made up 16.5% of the market in 2013 (as opposed to three companies making up 75.1% in the US). 60% of domestic N fertilizer producers are small-scale enterprises, intensifying competition and keeping industry concentration low (IBISWorld, 2013b).

The fertilizer subsidies currently provided to farmers require extensive reform to make the RE targets presented above achievable. If the Chinese government were to redirect fertilizer subsidies towards technological innovation and environmental programs it could potentially incentivize farmers to improve N management and improve NUE. Improvements in technical capacity, for example through an extension network, would provide better information to farmers on fertilizer and manure best management practices. An example of an intermediary measure is the same type of conservation compliance mechanism described above for the US, making all or a portion of farmer fertilizer subsidies conditional on improvements in N management. By contrast, a fertilizer tax would have to be extremely high to have any impact on farmer behavior,
with a recent study showing that the elasticity of demand for fertilizer has varied between -0.004 and -0.34 over the past ten years (Huang et al. 2012).

Another policy instrument specific to China is rural land reform involving the privatization of agricultural land that might become a major tenant of Chinese central government policy in the coming years and decades. By allowing farmers to own agricultural land, they may have more incentive to avoid the frequent pitfalls of limited tenure: unsustainable practices with short-term payoffs, such as the over-application of N fertilizer (Lohmar and Somwaru, 2012).

References


Agricultural Policy and the 2007 Farm Bill. Woods Institute for the Environment, Stanford University, USA.


IBISWorld. 2013a. Fertilizer Manufacturing in the US. IBISWorld Industry Report 32351


U.S Department of Agriculture Economic Research Service. 2014. Feed Grains: Yearbook Tables. Table 1 – Corn, sorghum, barley, and oats: Planted acreage, harvested


Zhou W. 2010. CO₂ emissions and mitigation potential in China’s ammonia industry. Energ. Policy. 38:3701-3709
Figure S1 - Kilograms of N applied per Megagram of corn produced annually in both the US (grey line) and China (black line) from 1990-2010. NUE has noticeably increased in the US, and decreased in China over this period.

Table captions

Table S1 - Average N application rates in (a) the United States and (b) China under the BAU, moderate, and ambitious NUE scenarios. Projected corn yields (Alexandratos and Bruinsma, 2012), and prices for corn, US natural gas, Japanese liquefied natural gas, coal, urea and N fertilizer (OECD/FAO, 2013; IEA, 2012) do not change across the different scenarios. BAU N application rates are taken from Alexandratos and Bruinsma, (2012).

Table S2 - Proportion of split vs. precision application (the two major FBMPs considered here) used to achieve the moderate and ambitious NUE scenarios in the US and China and the total cost per kg N reduced in each case. 5%-95% uncertainty bounds for prices are in brackets (Winiwarter (2013), personal communication). China’s RE 30% target requires a larger N rate reduction than precision application could generate according to GAINS (50% versus 33%). However, data shows that a 50% N rate reduction is feasible with precision agriculture (Koch et al. 2004), so we assume here that China’s RE 30% target is achieved with the 100% FBMP implementation strategy by using 100% precision application.
Table S3 - Expert elicitation responses on the current and future price and cost of production of enhanced efficiency fertilizers (split into slow/controlled release fertilizer (SCRF) and nitrification/urease inhibitor (NI/UI)) under the different RE scenarios for both the US and China. Responses are expressed as a percent premium above the price and production cost of traditional N fertilizer. The 5%-95% uncertainty bounds in brackets below each parameter represent the average of experts’ lower and upper bound estimates.

Table S4 – Example of the US weighting protocol for expert responses. The second column states the correct answer for each seed question (not applicable to Q1 and Q2 because they are questions about experience), the third column gives the range of expert responses for a particular question, and the fourth column gives the average of the weights given to experts for a particular question.

Table S5 - IPCC emission factors for the major forms of nitrogen pollution and the damage cost estimates associated with them (from Gu et al. 2012, Compton et al. 2011 and Brink and van Grinsven, 2011) adapted to US and China gross national income per capita. Standard deviations are noted in brackets below the average value for each Nr species.

Table S6 - Median 20-year economic impacts of the 100% EEF, 100% FBMP and 50/50 implementation strategies for the RE 50% and RE 60% targets in the USA and the RE 20% and RE 30% in China. All values are in 2005 USD billions. Environmental benefits dominate across all scenarios and implementation strategies.

Tables

Table S1a

<table>
<thead>
<tr>
<th>Year</th>
<th>Nitrogen application rate</th>
<th>Corn yield</th>
<th>Corn price</th>
<th>USA natural gas price</th>
<th>N price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BAU</td>
<td>Moderate</td>
<td>Ambitious</td>
<td>(Mg ha⁻¹)</td>
<td>($2005 Mg⁻¹)</td>
</tr>
<tr>
<td>2010</td>
<td>157</td>
<td>157</td>
<td>157</td>
<td>10.0</td>
<td>181</td>
</tr>
<tr>
<td>2015</td>
<td>158</td>
<td>158</td>
<td>158</td>
<td>10.1</td>
<td>184</td>
</tr>
<tr>
<td>2020</td>
<td>159</td>
<td>156</td>
<td>149</td>
<td>10.2</td>
<td>201</td>
</tr>
<tr>
<td>2025</td>
<td>161</td>
<td>152</td>
<td>139</td>
<td>10.4</td>
<td>209</td>
</tr>
<tr>
<td>2030</td>
<td>162</td>
<td>150</td>
<td>131</td>
<td>10.5</td>
<td>219</td>
</tr>
<tr>
<td>2035</td>
<td>162</td>
<td>147</td>
<td>122</td>
<td>10.7</td>
<td>230</td>
</tr>
</tbody>
</table>

Table S1b
### Table S2

<table>
<thead>
<tr>
<th>Year</th>
<th>United States</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moderate NUE</td>
<td>Ambitious NUE</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Split</td>
<td>Precision</td>
</tr>
<tr>
<td></td>
<td>86%</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td>22%</td>
<td>78%</td>
</tr>
<tr>
<td></td>
<td>19%</td>
<td>81%</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>100%</td>
</tr>
</tbody>
</table>

### Table S3

<table>
<thead>
<tr>
<th>Product</th>
<th>2014 price premium</th>
<th>2014 cost premium</th>
<th>2035 price premium</th>
<th>2035 cost premium</th>
<th>2035 price premium</th>
<th>2035 cost premium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow/controlled release fertilizers</td>
<td>29% (24%-158%)</td>
<td>23% (18%-54%)</td>
<td>24% (18%-36%)</td>
<td>17% (12%-31%)</td>
<td>21% (15%-33%)</td>
<td>16% (12%-31%)</td>
</tr>
<tr>
<td>Nitrification/urease inhibitors</td>
<td>16% (15%-25%)</td>
<td>6.8% (4%-12%)</td>
<td>13% (11%-20%)</td>
<td>4.8% (2%-8%)</td>
<td>11% (7%-17%)</td>
<td>4.7% (2%-8%)</td>
</tr>
<tr>
<td>Weighted average</td>
<td>17% (16%-34%)</td>
<td>7.9% (5%-15%)</td>
<td>17% (14%-26%)</td>
<td>9.3% (6%-17%)</td>
<td>15% (11%-24%)</td>
<td>10% (6%-18%)</td>
</tr>
</tbody>
</table>

### Table S4

<table>
<thead>
<tr>
<th>Question</th>
<th>Correct response</th>
<th>Range of responses</th>
<th>Average of weights</th>
</tr>
</thead>
</table>

39
Table S5

<table>
<thead>
<tr>
<th>Nr</th>
<th>compound</th>
<th>IPCC emission factor</th>
<th>USA</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Gu et al.</td>
<td>Compton et al.</td>
<td>Brink and van Grinsven</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$(2005 \ \text{kg N}^{-1})$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q1</td>
<td>N/A</td>
<td>6-33 years</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Q2</td>
<td>N/A</td>
<td>Yes/No/Partially</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>Q3</td>
<td>27%</td>
<td>30%-66%</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>Q4</td>
<td>12%</td>
<td>2%-30%</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>Q5</td>
<td>5</td>
<td>2-8</td>
<td>0.73</td>
<td></td>
</tr>
</tbody>
</table>

* Uncertainty ranges were not reported for these specific estimates in the original publications.
<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>RE 50%</th>
<th></th>
<th></th>
<th>RE 60%</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100% EEF</td>
<td>100% FBMP</td>
<td>50/50</td>
<td>100% EEF</td>
<td>100% FBMP</td>
<td>50/50</td>
</tr>
<tr>
<td>$2005 billions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>USA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farmers</td>
<td>1.0</td>
<td>1.2</td>
<td>1.1</td>
<td>3.0</td>
<td>-0.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Industry</td>
<td>-0.7</td>
<td>-1.2</td>
<td>-1.0</td>
<td>-2.2</td>
<td>-1.1</td>
<td>-1.7</td>
</tr>
<tr>
<td>Environment</td>
<td>46</td>
<td>46</td>
<td>46</td>
<td>115</td>
<td>115</td>
<td>115</td>
</tr>
<tr>
<td><strong>China</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Farmers</td>
<td>6.4</td>
<td>1.1</td>
<td>3.8</td>
<td>15.0</td>
<td>-1.5</td>
<td>6.7</td>
</tr>
<tr>
<td>Industry</td>
<td>-0.6</td>
<td>0.7</td>
<td>0.1</td>
<td>-2.9</td>
<td>2.7</td>
<td>-0.20</td>
</tr>
<tr>
<td>Environment</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>